11th International Conference on Indium Phosphide and Related Materials
16-20 May 1999 Davos, Switzerland

InP-BASED THERMIONIC COOLERS

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Abstract

Thermoelectric coolers are important elements of many optoelectronic systems. Current commercial coolers are based on non-conventional semiconductors such as BiTe. In this paper we analyze the prospect of InP based material to fabricate coolers that can be integrated with optoelectronic components. Experimental results are shown where thermionic emission current in InGaAs/InGaAsP heterostructures is used to enhance the cooling power of conventional bulk material. About one degree cooling over 1 μm thick barrier is observed (i.e. a cooling power of 200-300W/cm^2). Calculations for InGaAs/InAlAs superlattices show that single stage cooling by as much as 20-30 degrees should be possible.

I. Introduction

Conventional thermoelectric (TE) coolers are based on Peltier effect at metal/semiconductor junctions. When electrons flow from a material in which they have an average transport energy smaller than the Fermi energy to another material in which their average transport energy is higher, they absorb thermal energy from the lattice and this will cool the junction between two materials. In a linear transport regime, the overall performance of TE cooling devices can be expressed as a function of the dimensionless figure of merit $ZT= S^2\sigma T/ß$, which describes the interplay between the Peltier cooling at the junctions given by the Seebeck coefficient S, Joule heating in the material given by electrical conductivity σ, and heat conduction from the hot to the cold junctions given by coefficient of thermal conductivity ß [1]. Current state-of-the-art thermoelectric material for cooling at room temperature is based on Bi_2Te_3. This material was discovered in 1950's, it has an efficiency 7-10% of the Carnot value, and maximum single-stage cooling of about 70°C. Bulk III-V semiconductors have much smaller ZT values. Maximum cooling reported for InP and GaAs TE coolers is on the order of 4-8°C [2-5].

In this paper we describe a method based on thermionic emission in heterostructures, where cooling power and efficiency can be significantly improved [6-10]. In thermionic emission process, hot electrons from a cathode layer are selectively emitted over a barrier to the anode junction. Since the energy distribution of emitted electrons is almost exclusively on one side of Fermi energy, when current flows, strong carrier-carrier and carrier-lattice scatterings tend to restore the quasi-equilibrium Fermi distribution in the cathode by absorbing energy form the lattice, and thus cooling the emitter junction. The performance of the device can be optimized at various temperatures and for different cooling powers by changing the height and thickness of the barrier layer.

Monte Carlo simulations of nonisothermal transport across InGaAs barriers shows that thermionic cooling can maintain a temperature gradient of 10 degrees over a distance of 2 μm and provide a net cooling power of about 700 W/cm^2 [7].

II. Bulk InGaAsP thermionic cooling

In order to investigate this effect experimentally, a single InGaAsP (λ_{gap}=1.3 μm) barrier surrounded by n$^+$ InGaAs cathode and anode layers was grown using metal organic chemical vapor deposition (MOCVD). Cathode and anode layer thicknesses were 0.3 and 0.5 μm and they were doped to 3×10^{18} cm^{-3}. The barrier layer had an n-doping of 2×10^{17} cm^{-3} and was 1 μm thick. Mesas with an area of 90x180 μm^2 were etched down using dry etching techniques. Ni/AuGe/Ni/Au was used for top and bottom contact metallization. Fig. 1 displays the temperature on top of the device as a function of current at various

0-7803-5562-8/99/$10.00

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **1999**	2. REPORT TYPE	3. DATES COVERED **00-00-1999 to 00-00-1999**
4. TITLE AND SUBTITLE **InP-Based Thermionic Coolers**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Baskin School of Engineering,University of California,Santa Cruz,CA,95064**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**		**3**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

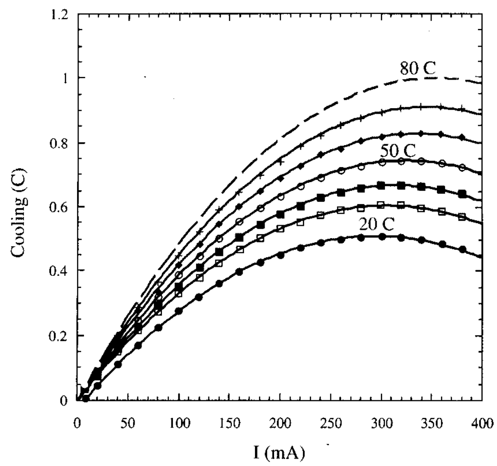

Fig. 1 Measured temperature on top of the thermionic cooler at various heat sink temperatures.

substrate (heat sink) temperatures. We noticed a rise in the substrate temperature (by about 0.2-0.4°C) that is an indication of the relatively high thermal resistance of the ceramic package and the soldering layer used to mount the sample. Despite the poor performance of the heat sink on the anode side, a net cooling of 0.5°C is observed on top of the device at 20°C heat sink temperature. This cooling over 1 μm thick barrier corresponds to cooling capacities on the order of 200-300 W/cm^2.

III. High barrier superlattice thermionic cooling

One can further improve the cooling power by using tall barriers in highly degenerate InGaAs material (Fig. 2). In this case, the increase in number of carriers near the Fermi energy in conjunction with selective

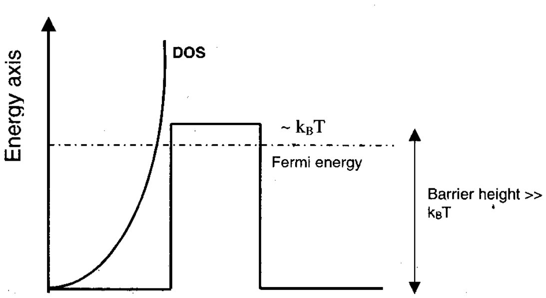

Fig. 2 Tall barrier heterostructure integrated thermionic cooling.

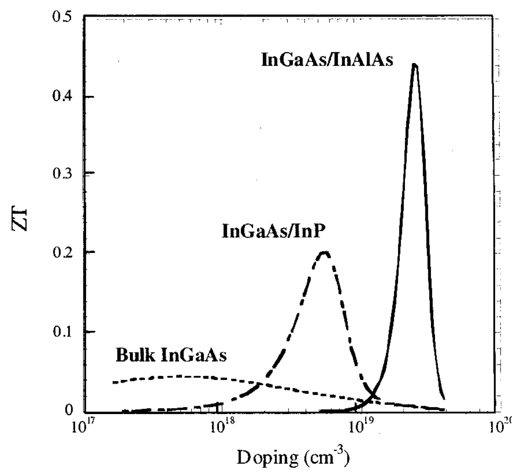

Fig. 3 Theoretical thermoelectric figure-of-merit (ZT) for bulk InGaAs and for high barrier heterostructure thermionic coolers based on InGaAs/InP and InGaAs/AlGaAs at various doping densities. The order-of-magnitude improvement in ZT is purely due to thermionic emission of hot carriers above the barrier.

emission of hot electrons, improves the efficiency of the device substantially. Fig. 3 displays the thermoelectric figure-of-merit for bulk InGaAs as a function of doping. The experimental doping dependence of electron mobility is included in the calculations. This figure shows also the expected ZT for multibarrier structures with tall InP (ΔEc=0.24 eV) or InAlAs (ΔEc=0.51 eV) barriers. The order of magnitude improvement in ZT is due to large increase in Seebeck coefficient at high doping densities in multibarrier devices. The thermal conductivity of the composite material is taken to be 5 W/mK, i.e. identical to the bulk InGaAs. Several recent studies [11-13] have shown that superlattice thermal conductivity is also reduced comparing to bulk value, so further improvement in ZT is expected.

In the above analysis quasi diffusive transport of electrons above the barriers is assumed. We do not expect significant changes in the device performance due to the finite electron energy relaxation length. In fact, corrections due to ballistic transport will tend to improve the cooling characteristics even more.

Fig. 4 shows the calculated net cooling as a function of current for bulk InGaAs and for high barrier heterostructure thermionic coolers based on InGaAs/InP and InGaAs/AlGaAs. The devices have an area of 2500 μm^2 and they are 10 μm thick. Heat generation in the gold wire connected to the cold side is taken into account as well as finite thermal conductivity of the InP substrate at

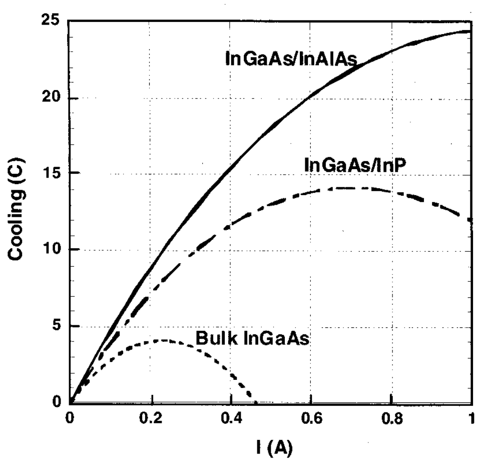

Fig. 4 Calculated net cooling as a function of current for bulk InGaAs (n-doped $5x10^{17}cm^{-3}$) and for high barrier heterostructure thermionic coolers based on InGaAs/InP (ΔEc=0.24eV, n-doped $5x10^{18}cm^{-3}$) and InGaAs/AlGaAs (ΔEc=0.51eV, n-doped $2.5x10^{19}cm^{-3}$).

the anode side. The gold wire is assumed to be 250 μm long with 1 mil diameter. The InP substrate is 100 μm thick and has a thermal conductivity of 68 W/mK. One can see that single stage cooling by as much as 20-25°C is possible with high barrier thermionic coolers.

IV. Summary and conclusion

Thermionic emission cooling in single barrier InGaAsP-based heterostructures is investigated experimentally. Cooling on the order of a degree over 1 μm thick barriers has been observed. Calculations for high barrier, highly degenerate InGaAs/InAlAs superlattices show that single stage cooling by as much as 20-30 degrees should be possible.

Acknowledgments

The authors would like to acknowledge many stimulating discussions with Prof. Venky Narayanamurti, and Dr. D.L. Smith. This work was supported by DARPA and the Office of Naval Research under the contract 442530-25845.

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